# The science of growth and the growth of science

*Suranjana Nabar-Bhaduri and Sumit Bhaduri*

*Science, technology and economics share complex relationships and attempts to quantify the contribution of science and technology (S&T) to economic growth are fraught with many difficulties. The growth in S&T related activities on the other hand could be quantified in terms of number of publications and patents. Do such numbers for an area of S&T that has had clear and quantified economic impact throw any new light on their relationships? With 'Green Revolution' as the test case and publication and patent data of the last 25–40 years, such an analysis has been carried out. It appears that the practice of S&T in this area has been greatly influenced by the intellectual property rights related aspects of globalization.*

Does progress in science and technology (S&T) automatically lead to economic growth or is it the other way round, i.e. that investments made in S&T are productive, provided there is economic growth? If this sounds like a chicken and egg question, consider the answers that may be offered by a scientist on the one hand, and an economist on the other. A scientist would probably claim that without science there would be no technology and that without technology industrial growth is not possible. He may give historical examples to substantiate his argument. He may point out that each of the four major economic booms of the last two hundred years were caused by progress in technology. First, it was the steam engine; second, the railroad programmes accompanied by developments in steel and coal technologies; third, electric power and automobile technology, and the fourth was due to fossil oil-based technologies.

The economist may generally agree with all this, but point out that what makes economic growth possible is a much-debated question with no simple answer. From a really long-term point of view, geography may well be the critical determining factor for a whole host of conditions that make economic growth possible[1]. A strong base in S&T may be a necessary but certainly not a sufficient condition for growth. All rich countries in today's world do not necessarily have a spectacularly strong base in S&T. The economist may also smile indulgently at the historical examples of steam engines, etc. and point out that these so-called long business cycles of 50–60 years, or Kondatriev cycles as they are commonly known, may well just be figments of imagination. There are a large number of respected economists who do not believe in such long business cycles.

This inconclusive debate may well go on but it is worth pointing out that globally, and India is no exception, the expectation of economic benefits from S&T runs deep among the policy makers. Such expectations, reasonable though they may be, ignore some vital details. First, the primary function of science is the generation of knowledge and hopefully good quality, non-trivial knowledge. The value of all such knowledge cannot be measured in monetary terms. Technologies that contribute to economy are tangible and immediate manifestations of science, but to equate all science with technology would be a gross mistake. A bigger mistake would be to think that all good science could somehow be converted into commercially viable spectacular technologies that drive economic growth. Secondly, the economic and societal impacts of a given technology are invariably dependent on the rate at which it is accepted, if it is accepted at all. In the relationship between S&T and economics, diffusion of technology, rather than the availability of a given technology, often is the critical factor[2]. Finally, there are just too many examples to show that real technological breakthroughs come from high quality, curiosity-driven, and in most cases, unfashionable areas of S&T.

It is for these and related reasons that the quantification of the positive impact of technology on economic growth continues to be one of the most challenging and active areas of research in economics. The general approach is to express the output of an economy as a function of inputs such as capital, labour and 'technology', and to look at the growth rate. As 'technology' input is not something that can be directly measured, to determine what part of the overall growth is due to the technological progress, the parts that are due labour and capital are deducted from the overall rate of growth. Computed in this way, the growth attributable to 'technological progress' is called the 'Solow residue'.

In 1957, Robert Solow was the first economist to analyse the causes of productivity gains and break them down into several categories[3]. Specifically, Solow analysed data pertaining to the growth rate of the GDP in the US for the period 1909–49. The results of his analysis indicated that of the 2.9% average annual growth rate in the GDP of the US for the period 1909–1949, 0.32% was attributable to capital accumulation, 1.09% to increases in the labour input, leaving as much as 1.49% to technological progress. Over the years, the Solow model has undergone many refinements and modifications. It is now generally agreed that the empirical performance of the Solow model improves, if human capital is included as an input.

The tangible and directly measurable outputs of most S&T-related activities are documents – papers, patents, etc. Do analyses of S&T-related activities measured by the change in these outputs over time help us to understand their effect on economics and vice versa? This commentary is written from such a perspective. Here, we look at the change in output data for an area of S&T, the socio-economic impact and relevance of which are well established. In recent times, in the efforts to make S&T competitive and more productive, data on publication and patent outputs are often used[4]. The purpose of this commentary is to see to what extent the number of publications, patents and citation analyses in a given area correspond to their perceived relevance and/or proven impact on economic growth.

## Outputs of S&T – publications, patents and citations

The direct outputs of all knowledge workers including scientists are usually peer-reviewed papers and other scholarly communications. In experimental sciences, publications serve the function of providing details that allow others to duplicate the experiment, if they so desire. Should there be more than one claimant for a given discovery, they also help settle conflicting claims. In the history of science and also in recent times, there have been many instances of abuse and dubious interpretation of both these functions[5]. Another parameter called 'citation analysis', invented and popularized by Eugene Garfield, has acquired importance in recent times. This is basically an analysis of how many times a specific publication is cited by other researchers over a given period of time. Citation analyses are often used as 'the' technique to measure and rank the importance of publications and journals[6]. With the advent of computers, huge databases have come into existence. Full publication records and citation analysis in all mainstream journals are now routinely available from such databases.

The esteem that a scientist enjoys from fellow scientists and his ability to attract research funds, now increasingly depend on his overall publication records as well as citation analysis. According to Frank George, author of the book *Economy of Attention*[7], 'scientific communication may be a "chase after attention", but it happens because scientists "invest their own attention in order to get attentive returns".' He goes on to hypothesize that citation analysis is similar to the 'invisible hand' of a market mechanism that guides the efficient use of attention. Whatever may be the complex sociological and/or psychological reasons behind a knowledge worker's preoccupation with publications and citations, these are the immediate, tangible and quantitative output of academic scientific research. The total number of publications and citations over a given period of time in a given area is a quantitative measure of the interest of the S&T community in that particular area.

The other direct measurable outputs of technology-oriented scientific activities are patents. When research yields results (or inventions as they are commonly called) that have reasonable application potential, then patents are taken. The history of patents goes back to 1449, when King Henry VI awarded a patent on the manufacture of stained glass. Modern patents are costly and the legal rights associated with a patent have fixed lifetimes. The patent authorities evaluate the novelty, non-obviousness and usefulness of the inventions before granting patent rights.

In earlier times, the patent laws in different countries had significant differences. One of the much-discussed effects of globalization and Trade-related Aspects of intellectual property rights (TRIPS; see later) has been a drastic reduction in such differences. Once a patent is granted, there are periodic charges for maintaining the legal rights of the patent over its lifetime. Because of the costs involved, it is not surprising that a large majority of the existing patents are owned by industries. It is also not surprising that many companies when under pressure to make their businesses more profitable try to sell idle patents, i.e. patents that are not commercialized. A few hundred patents and a few thousand papers may cover a single well-established technology and usually out of all these documents, only a few are of critical importance. It is a common strategy adopted by most companies to patent inventions, not because the inventions are or could be commercialized, but because such patents keep competitors away from that line of approach.

## The test case – Green Revolution

The success of the high-yielding varieties of crops obtained by careful plant breeding in raising the production of wheat and rice to two- to threefolds of their normal yields, is what is commonly referred to as the Green Revolution. Its origin could be traced back to the 1940s when Norman Borlaug, a Nobel Peace Prizewinner, joined Rockefeller Foundation and over the next several years led efforts directed towards obtaining high-yielding varieties of crops, specifically high-yielding dwarf wheat. This was followed by a massive diffusion of technology that involved making the high-yielding varieties of rice and wheat available to farmers, and eventually the widespread acceptance and adoption of these crops in Latin America and Asia. We have chosen Green Revolution as the test case for obvious reasons. Good data on the economic impact of Green Revolution have recently become available. It is also an established fact that the agriculture-related S&T drive as it happened before and during the Green Revolution, and the economies of the agricultural sectors of a number of developing countries, have been and continue to be strongly correlated.

A detailed study on the economic impact of Green Revolution has recently been carried out[8]. This study analyses the impact of international research for 11 major food crops by region and country for the period 1960–2000. The economic impacts of this remarkable S&T effort are found to be as follows. First, a distinction is to be made between an 'early Green Revolution' period and a 'late Green Revolution' period. In the early period (1960–80), high-yielding crops contributed substantially to growth in Asia and Latin America, but relatively little in other areas like the Middle East–North Africa and Sub-Saharan Africa. The largest initial impacts in wheat and rice were in irrigated areas and in rainfed lowlands with good water control.

For all developing countries during this period, these crops accounted for nearly 17% of the increases in production. In the late Green Revolution period, the contribution of these crops to production growth was almost 40% for all developing countries. Thus during the late Green Revolution period, production gains were more dependent on high-yielding crops than in the early period. The use of fertilizers and irrigation contributed only modestly to the increase in productivity. Through simulation, this study also highlights the welfare effects of the Green Revolution and the importance of international research in the success of the programme. What then have been the trends in scientific outputs, i.e. publications, patents and citations, in the area of plant breeding over this long period?

## Green Revolution – publications and patents

As might be expected, accumulated outputs of the knowledge industry are voluminous. The total number of publications in the 'isiwebofknowledge' database is more than 30 million and the total number of patents in the United States patent office is more than 6.5 million. Till the end of 2004, out of these documents, more than 1900 papers and 2700 patents dealt with plant breeding. However, the relative magnitude of S&T outputs during the early and late Green Revolution periods

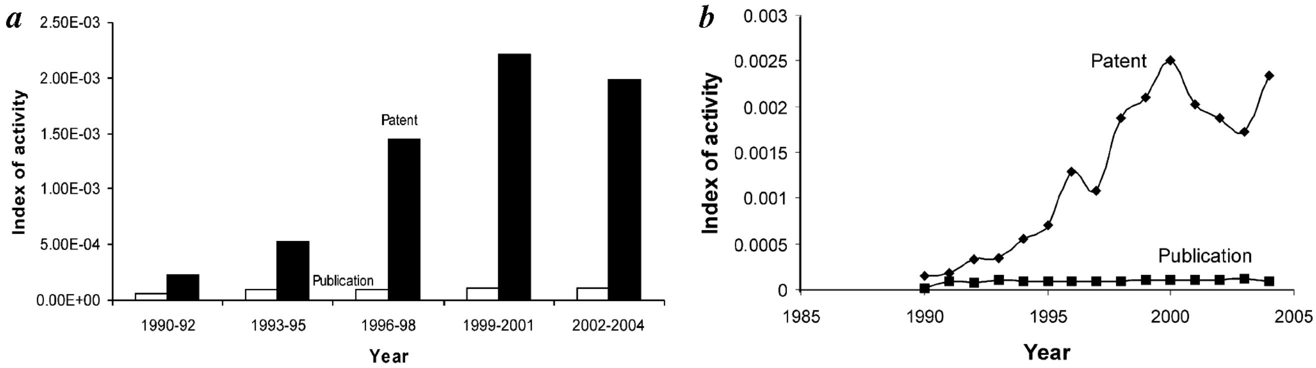


**Figure 1.**

is remarkably different. During 1960–80, only about 200 papers on plant breeding were published and 30 patents were issued. In contrast, during 1980–2000 the number of papers and patents on plant breeding was approximately 1200 and 1450 respectively.

On closer scrutiny, it turns out that the rise in the number of publications and patents is rather modest till the early nineties. Rapid increases are observed only from about the mid-nineties. Thus, in 1990 only eight patents were issued and 17 papers published. The corresponding numbers for 2000 are 400 and 111; a staggering 50 and a notable 6.5 fold increase respectively. To see if these increases actually reflect growing activity specifically in the area of plant breeding, it is necessary to account for the increases in the total S&T outputs, i.e. outputs for all areas of S&T. Figure 1 *a* shows how the number of patents and publications dealing with plant breeding has changed in comparison to the total number of patents and publications per three-year block, from 1990 to 2004.

A few points about the data shown in Figure 1 *a* are to be noted. First, the ratios obtained by dividing the number of publications ($P_1$) or patents ($P_2$) in the area of plant breeding over a fixed period of time by the total number of publications ($T_1$) or patents ($T_2$) for that particular period, are indices of S&T activities. The two indices, $I_1$ ($= P_1/T_1$) and $I_2$ ($I_2 = P_2/T_2$), therefore reflect the activities as documented in the publication and patent databases respectively. Thus, $I_2$ for the three-year block 2002–04 is approximately ten times that of 1990-92, while the corresponding increase in $I_1$ is about twice. Second, the index of patent activity has been consistently higher, on an average ~13 times, than that of the publication activity. Figure 1 *a* indicates this, but it can be seen more clearly in Figure 1 *b*, where the index of activity for every year is plotted against the year.

The commercial potential of research in the area of plant breeding has thus been well recognized from the early nineties. A few ups and downs are observed for both patent (Figure 1 *b*) and publication activities (see later), but the growth of patent activity is substantially more than that of publication activity.

The spurt in S&T activities in plant breeding coincides with the culmination of the Uruguay Round of negotiations, under the General Agreement on Tariffs and Trade (GATT) among more than 100 countries. The negotiations started in 1986, the first draft of a final legal agreement was put on the table in Geneva in December 1991, and the World Trade Organization (WTO) was created on 1 January 1995. TRIPS agreement came about as a part of Uruguay Round of negotiations and among a variety of topics that were covered, genes of wild rice, etc. were also included.

It is reasonable to ascribe the frenzied increase in patent activity to these much talked-about drivers of globalization. To companies selling agro products, the commercial potential of high-yielding plants and seeds that could be covered by patents and marketed globally was obvious. The underlying science that made this increased patenting activity possible was genetics in general and plant genetics in particular. Many of the patents of the late seventies and early eighties describe conventional methods of plant breeding, where detailed descriptions on origin, asexual reproduction and summary of the particular variety of the plant are given. The major patent on genetic engineering appeared in 1980 and the first patent in the area of plant breeding where DNA is explicitly mentioned was issued[9] in 1983.

To look at the changes in the index of publication activity over a longer period of time, the index of publication activity ($I_1$) for every five-year block is plotted for 40 years (1965–2004) in Figure 2. The midpoints of the five-year blocks, e.g. 1967 for the period 1965–69, are used as the *x*-axis data. It is clear that publication activity remained more or less constant from about 1970 to 1985, but after that there was a marked increase till the early nineties. Over the last decade there has been a slowing down in the growth of publication activity.

The increased publication activity from the mid-eighties must have been caused by the progress in plant genetics. The recent slowing down of growth in publication activity could be for many reasons and detailed discussions on the probable reasons are beyond the scope of this commentary. One of the reasons most probably is that entirely new problems, genome-based techniques etc., that may propel publishable new research or open up new directions have been slow in coming. Also, research funding from non-company sources might not have been enough to sustain new research. In any event, gene-related discoveries played an obvious role in triggering growth both in patent and in publication activities. Further support for this view comes from the time-dependent citation patterns of two highly cited papers in the area of plant breeding. The paper by Finlay and Wilkinson, published in 1963, deals with conventional plant breeding[10]. It has been cited more than a thousand times. The paper by Flor, published in 1971, has been cited more than 650 times and it deals with plant genetics[11]. As can be seen from Figure 2, while the citation activity

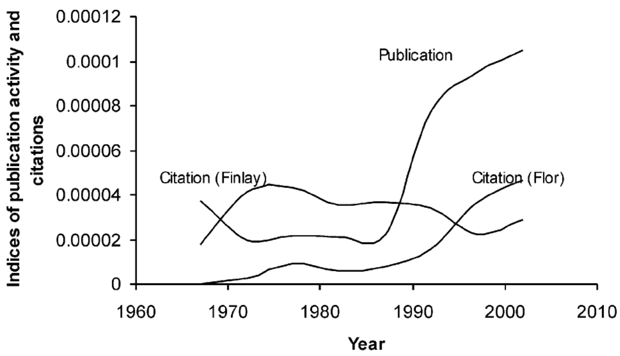


**Figure 2.**

index (number of citations per year/total number of publications per year) for the Finlay paper has remained more or less constant, for the Flor paper there has been an increase. The upward movements of the citation activity index of the Flor paper and publication activity index are remarkably similar.

Two other points need to be mentioned. Publication data from 1955 onwards are available in the Web of Science. If those data are used, a hump with a peak in the later half of the sixties is observed. In Figure 2, the right shoulder of this hump can be seen. The increase in publication activity in the late sixties coincides with the first encouraging reports from the Indian subcontinent. In other words, the first signs of success of the early Green Revolution had also spurred new research in plant breeding. Finally, though the publication data used in Figures 1 and 2 are global, a similar trend is observed using publication data on plant breeding only from the US ($I_1$ = publication on plant breeding from the US per year/total number of publications per year). The absolute values of $I_1$ are of course much smaller in this case, but the overall trend in global and the US publication activity indexes over the years are similar.

## Conclusion

The inferences that may be drawn from the above analyses are as follows. First, although globalization and TRIPS by themselves have little to do with science, they have had profound and irreversible impacts on an area of science that is, rightly or wrongly, considered to have huge commercial potential. It is worth remembering that almost all of the pioneering work that made Green Revolution possible was not patented, and making profit was not the driving motivation. The most visible aspect of globalization has been the shrinking sphere of influence of nation states and the global search by private capital for new markets. The intense patent activity in plant breeding is a manifestation of that search. It is tempting to compare the soaring index of patent activity with that of a stock market on a bull run – fuelled in both the cases by 'irrational exuberance'. The ultimate commercial fate of genetically modified (GM) food and plants will be determined less by the hype and splendour of the new technology and more by societal acceptability[12]. Advertisements, political pressures, etc. will undoubtedly have an effect on the eventual commercial fate of GM technology, but hopefully a careful and objective risk-benefit analysis will also find a place somewhere.

The example discussed above also shows the inadequacy of the linear model of 'science to technology'. It shows that a technological success story can have a positive impact on the underlying science. Science to technology is not a one-way traffic; a technological success with visible socio-economic benefits can spur further research in the areas of science on which that technology is based. The increases in publication index both in the late sixties and over the last decade were partly due to the good news that the Green Revolution was a success. However, the increases in both the activity indexes for publications and patents over the last decade or so were possible mainly because of independent advances in genetics. This networked structure, where several branches of science and technology merge together to push away the boundaries of an existing technology, is a general phenomenon and indicative of the trajectory of all future S&T.

Finally, a word about the methodology adopted here. The results show that a detailed analysis of publication and patent activity does bring out the relationships between the developments in a specific area of S&T and the dominant socio-economic forces within which they operate. The method is a general one that in principle could be applied to many other areas, and we hope to do so in future; but it also has an obvious limitation. Reliable and easily accessible output data of S&T are available only for about the last fifty years. Anything which goes back beyond that will probably be outside the scope of this type of analysis.

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*Suranjana Nabar-Bhaduri is in Uniqema (ICI India) and Sumit Bhaduri* is in the Reliance Industries, Swastik Mills, V N Purav Marg, Chembur, Mumbai 400 071, India. *e-mail: sumit_bhaduri@ril.com*